ELECTRICALLY CHARGED WATER MISTS FOR EXTINGUISHING FIRES

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SUMMARY

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A brief experimental fire suppression study found that electrical charging of water mist can substantially reduce both the time and the amount of water required to extinguish a pool fire. Another benefit of charging was an increased spraying angle, which occurs even for low pressure sprays. It was also found that much lower voltages than reported by other workers can be very effective in charging the mist and extinguishing fires. The specific objectives of the study were to: (1) compare the motion of charged and uncharged water mist droplets near a flame and (2) determine the reduced time for fire extinguishment due to electric charging of the water mist. The current program addressed ceiling sprinkler extinguishment of compartment fires, and the same principles should hold for aircraft engine nacelle fires. The main technical problem encountered was achieving a uniform distribution of water mist over a significant surface area both with and without charging. Promising results were obtained despite this difficulty which can be corrected with additional work. This study has achieved the objectives of element 4d of the Next Generation Fire Suppression Technology Program and additional funding should be provided to optimize the technology and demonstrate its effectiveness on larger scale fires.

I. INTRODUCTION

A. BACKGROUND

The technical basis for this program originated with Dr. Stuart Hoenig at Associates in Applied Research, Inc., AARI. He suggested that his experience with water droplet charging and AeroChem's experience with electric field effects on flames could be utilized to demonstrate that an electrically charged water mist would extinguish a fire more efficiently than an uncharged mist. Basically, less water would be needed if the charged droplets were attracted to the fire. The original motivation for the concept was the extinguishment of conventional civilian sector fires by generally horizontal water streams in regions such as the Southwest and rural areas having limited water resources. Under NGP sponsorship, the program was directed towards the application of water mist charging to Navy compartment fires using ceiling sprinkler systems.

Because of the limited amount of time and funding available, the focus of the program was on demonstrating that electric charging of the water mist produces a beneficial effect on small scale fires. The results obtained indicate that there is indeed an improved performance. Additional time and funding are needed to validate and extend these results, and more importantly, to better understand the basic mechanisms, optimize the charging technique, and test the approach on larger scale fires.

B. EFFECTIVENESS OF WATER MIST

Water mist is highly effective in suppressing fires. For example, it has been shown that considerably less mist (by mass) is needed to extinguish a pool fire [Ndubizsu et al, 1997] compared to nitrogen. The prime reasons for this effectiveness are the rapid evaporation of the small water droplets which enhances cooling of the fire, oxygen displacement by the water vapor, and absorption of radiant energy [Mawhinney et al, 1994]. However, the small size of mist droplets can also be detrimental if the droplets do not have sufficient momentum to reach the fire due to air currents induced by the fire plume. For this reason, the idea of using a charged mist to take advantage of the electrical properties of flames to increase the number of droplets near a fire was proposed, and this was the major thrust of the current program.

C. FLAME IONIZATION

It is well known that hydrocarbon flames contain electrical charges because of the process of chemiionization [Calcote, 1962]. In chemiionization, flame radicals react to form electrons and positive ions at temperatures much lower than those required for thermal ionization. This is the principle behind flame rods which detect the presence of a flame in industrial burners through a measured electrical current. In a normal flame both positive and negative ions (primarily formed by electron attachment) are formed in addition to the electrons. The high mobility of the electrons results in the outer region of the flame being negatively charged by the electrons and the bulk of the flame region being positively charged by the preponderance of positive ions.

Much of what is known about flame ionization has been learned from studies of premixed flames. Calcote [1962] found that the maximum ion concentration at low pressures varied little for premixed flames composed of various fuels such as methane, propane and ethylene while significantly higher levels were attained with acetylene. The ion concentrations were higher at atmospheric pressure, on the order of 10^{11} ions/cc, with the differences between methane [Wortberg, 1965 and Peters et al, 1969] and propane [Calcote, 1963] being relatively small.

The peak ion concentration for an atmospheric pressure, methane-air diffusion flame was found to be in the same range as that for the atmospheric pressure premixed flames discussed above [Calcote et al, 1988]. We are not aware of ion concentration measurements for liquid fuels.

For real fuels and real fires (almost always diffusion flames) there are a number of considerations which could lead to either increases or decreases in the flame ionization, but these cannot be quantified at this time. For example, real fuels contain impurities (e.g., metals) which can greatly increase the ion concentration. On the other hand the formation of soot particles in cooler regions of a fire act as sites to which electrons will attach. This keeps the negative charge closer to these regions of the fire than would occur if the electrons were free to diffuse away on their own. Thus, electron attachment may reduce the charge separation (at least in the fire plume) that normally makes flames appear to be positive.

While it cannot be certain which effects will dominate in real fires, there is no doubt that diffusion flames in air behave as though they are positively charged since they are strongly pulled by negatively charged objects. This has been demonstrated when the fuels are ethylene [Payne and Weinberg, 1959], methane [Berman et al, 1987], propane, oil, wood and paper [Hoenig, 1995].

D. ELECTROSTATIC INTERACTIONS

The application of an external electric field in the vicinity of the flame results in the motion of electrons and negative ions towards the positive electrode and the motion of positive ions in the opposite direction towards the negative electrode. More momentum is generally exchanged by collisions between the positive ions and the neutral gas molecules as compared to the momentum exchanged by collisions with the negative species dominated by electrons. This momentum exchange results in the production of an ionic wind [Chattock, 1899] which is a flow towards the negative electrode. This ionic wind is responsible for the large flame displacements reported above, and the effect has been used to control blowoff stability [Berman et al, 1987], which can be increased or decreased depending on the orientation of the electrodes that produce the electric field. These effects can be produced with extremely low electrical power levels, on the order of 10^{-2} % of the power released during combustion [Calcote and Berman, 1991].

1. Relative Motion of Charged Mist and Fire

There are several different scenarios in which electric charging of the water mist droplets can interact with real fires. A negatively charged droplet approaching the vicinity of the fire will repel electrons and negative ions, and there will be an attraction between the negatively charged droplets and positive ions.

To distinguish whether the charged mist droplets move toward the flame or the flame moves towards the droplets, we computed the overall mass of water mist per unit volume in a spray based on assumed droplet velocities and compared it to the density of air under the assumption of a water application rate of 1 to 2 L/ (min-m^2), which is considered to be sufficient to extinguish a heptane pool fire [Patterson et al, 1996]. For example, the mass of the water mist droplets contained in a unit volume is 1.3% of the mass of air in the same volume for a water flux of 1 L/ (min-m^2) and a droplet velocity of 1 m/s. The water density relative to air varies proportionately with the water flux and inversely with the droplet velocity. The effective mass per unit volume of the ions is taken as the density of the air since the ions pull the air or other flame gases along with them when they move.

The mass of liquid water per unit volume can vary from a small to a moderate fraction of the mass of the flame gases per unit volume depending on the velocity of the droplets and the temperature of the gases. Of course, the actual droplet flux, and thus the liquid water mass, is decreased if the droplets are evaporating as they approach the flame. Thus, if the water flows are low and/or the droplets experience a great deal of evaporation near the flame, the droplet mass is low compared to that of the ions and the air that contains them so that the droplets can move towards the flame.

2. Current Flow Paths

Without a mechanism for charge removal, charge would build up and retard the attractive motion between the negative mist and the positive flame gases. This removal can be accomplished if there is an electrical ground in the vicinity of the fire. In many cases the circuit is closed by a conducting floor or wall in contact with the electrical ground. This would be the case for a fire on a ship deck or on metal shelving.

The voltage drop, ΔV, across a surface is given by

$$\Delta V = \rho \, t \, I/A \tag{1}$$

where ρ is the volume resistivity of any insulating layer such as paint, t is the thickness of the insulating layer, I is the total electrical current and A is the total surface area available through which current passes to ground. Because the currents involved in droplet charging are so small, and the surface area available for current flow to ground through floors and walls is so large, the voltage drop caused by current flow through wall or deck paint should be small. For aircraft applications such as fire extinguishment in engine nacelles, the surfaces are generally not painted so that there is no problem in obtaining a good electrical ground.

Even if the fire's net positive charge is small, the fire can still be a relatively better electrical conductor than the surrounding air due to the presence of charges in it. Thus, the droplets will still try to ground themselves through the fire, and the excess charge that they carry will eventually proceed to an earth ground near the base of the fire.

In addition to water droplets being individually drawn to the flame ions, the presence of a large number of charged droplets results in electrostatic repulsion between the droplets. An electrical ground allows a steady state current composed of the droplet charges to be established under the action of this self repulsion. The current path could be composed of droplets striking the floor or wall, droplets evaporating and the electrons they carry either passing directly to ground or attaching to a molecule which travels to ground under the influence of the charge induced electric field. Positive ions could move toward the droplets and neutralize them, leaving a net negative charge composed of the fire's electrons and negative ions which are discharged through the electrical ground near the fire's base.

The presence of cooler soot particles in the upper regions of a fire plume may act as sites for flame electron attachment. Repulsion of the negatively charged droplets by the negatively charged soot particles, could be beneficial from the point of view that those droplets might not be swept away by high velocity plume gases. If those droplets are redirected to lower velocity regions outside of the main plume, then they might be pulled in closer to the base of the flame by the positive flame ions or the presence of a surface electrical ground. In any case there are a number of possible situations in which electrical charging will cause water mist to come into closer contact with reacting flame gases.

E. SAFETY

Safety considerations present only a small concern with the droplet charging method used in this work because the currents involved in mist charging are extremely small. In this program two power supplies were used: a high voltage (15 kV) unit which is not capable of delivering any significant current (200 μA) and a lower voltage (5 kV) unit which can deliver 10 mA. The first unit is safe and the second unit can be made safe by installing current limiting resistors.

The high voltage manifests itself in the same manner as in science fair demonstrations in which people's hair stands on end when they are in contact with the voltage. While this is not life threatening in itself, any significant shock could be distracting or disorienting in an emergency situation. The only way such a shock could occur is by direct contact with the charged electrode. For this reason it is recommended that the high voltage electrodes be physically shielded to prevent direct contact with them.

Associates in Applied Research, Inc., AARI, has used power supplies similar to the first unit to charge water mist for dust suppression in industrial environments [Hoenig et al, 1976]. No adverse effects were experienced even though the nozzle operator was soaked with water during charged mist operation [Hoenig, 1995].

II. LITERATURE REVIEW

A. EXISTING DATA

Two references of particular interest for the present study are those of Patterson et al [1996], performed at the New Mexico Engineering Research Institute (NMERI), and Gottuck et al [1993], performed at Hughes Associates, Inc. Patterson et al [1996] obtained a large data base on mist extinguishment of heptane pool fires in a well-controlled test chamber environment. Although they did not study the charged mist case, their results are useful as a standard for comparison of the repeatability of data in similar experiments, and our data will be presented in a format similar to theirs. Gottuck et al [1993] compared fire extinguishment of heptane pool fires with and without electric charging.

Patterson et al [1996] used water mist to extinguish 5.08 cm diameter heptane pool fires in a 1.07 m x 1.07 m x 2.06 m chamber. Following establishment of the fire for 30 sec, the chamber was closed so that there was no further ventilation once the mist was turned on. In spite of their great care in achieving a uniform water flux over their chamber and the absence of ventilation currents, their data exhibits a tremendous amount of variability in extinguishment time as a function of water flux (Fig. 1), especially for low values of the flux. Since the data in this figure was extracted by us from their data plot, it may not be completely accurate, but it should provide a reasonable idea of the overall characteristics of their experiment. The curve shown is a cubic fit to the extracted data.

Gottuck et al [1993] studied the effects of electric charging of water mists on extinguishment of heptane fuel fires. A single mist nozzle was used in an open environment to extinguish a heptane fire in a 10 cm diameter pan. Water was collected to determine the water flux in the same size pan as used for the fuel.

Gottuck et al [1993] arbitrarily selected the criterion that a fire was considered to be extinguished if the extinguishment occurred within 20 sec after application of the water flow. They reported that this was a useful criterion for their experiments on the basis that fires that were not extinguished in that time were never extinguished, except for one case with electrical charging in which extinguishment occurred in 34 sec. Results were reported as groups of the number of cases in which a fire was extinguished out of the number of tests within a range of water collection rates for a given voltage.

Table 1 of this report reproduces the fire extinguishment results that appear in Table 3 of the report of Gottuck et al [1993] in the units of water flux used by Patterson et al [1996]. Their table shows three ranges of water mist flux and the fraction of the tests in which a fire was extinguished for each flux.

The major effect of charging occurs for the middle range of water flux in which 75% (3 out of 4) of the fires were extinguished by negatively charged droplets while only 46% (6 out of 13) of the fires were extinguished without charging and no (0 out of 3) fires were extinguished with positively charged droplets. The results not only show a beneficial effect due to negatively charged droplets but a detrimental effect of positive charging probably caused by positive ions repelling positively charged water droplets.

The negatively charged case was not tested at the highest water flux rate and no fires were extinguished for the lowest water flux according to the 20 sec criterion. However, 1 out of 3 negatively charged mists did extinguish a fire in 34 s in the lowest water collection range. Since this time was beyond their criterion of 20 s, it is recorded as a 0 out of 3 in their table. Since no tests were performed in this range for uncharged mists, it is impossible to make any comparison. However, if the results in the intermediate water collection range held up under more testing, this would certainly be a demonstration of a beneficial charging effect.

Data that we will present later corroborate the general features of the Gottuck et al [1993] data and show that extinguishment time rises steeply as water flux decreases. The data of Gottuck et al [1993] may have missed some of the intermediate values of water flux that could have extinguished fires in more than 20 s. It is also possible that their test environment's extinguishment time was extremely sensitive to water flow rate, making it more difficult for them to find intermediate values of water flux that produce finite extinguishment times.

The abstract of the report of Gottuck et al [1993] reads: "No significant increase in fire extinguishing capability resulted from charging the water sprays. The most notable effect of charging the spray was spray divergence that resulted in lower water application rates to the fire."

In spite of their "no significant increase" statement the data in Table 1 clearly shows that there is a very definite improvement in fire extinguishment due to charging water droplets in a range where extinguishment without charging becomes less effective as water flux is reduced. In the rest of the report we will clarify the conditions under which this improvement occurs and demonstrate the consistencies between their data, our data, and the uncharged mist data of Patterson et al [1996].

Their observation, presented in a negative vein, that charging makes the mist spread out can actually be beneficial since small uncharged droplets have short horizontal stopping distances which how far they can spread from the centerline of a spray nozzle. Charged droplets produce a force on each other that can disperse them to greater horizontal distances. Without charging, extremely high pressures would be needed or there would have to be an array of a great number of nozzles to achieve a wide distribution of fine water mist spray.

Gottuck et al [1993] were also concerned with the safety of the electrical system. The key requirement for safety discussed in the introduction was that the current be limited. There are inexpensive low power, low current systems available which will safely produce the voltage needed for charging, and additional safety features can also be built into any system.

B. IMPLICATIONS OF DATA FOR THIS STUDY

A major feature of the reports of both Patterson et al [1996] and Gottuck et al [1993] discussed above is the extreme variability of the data. For example, the data of Patterson et al [1996] for no charging in a well-controlled environment includes cases in which very small water flows extinguish fires in extremely short times (Fig. 1) while just a little additional water leads to extinguishment times on the order of minutes. This is difficult to understand based on direct physical principles. Similarly, the results of Gottuck et al [1993] are reported in a statistical format with the fire being extinguished in 20 sec in one instance and then, for the same water flow rate range, not being extinguished at all no matter how long the test time.

Although the data may clearly show definite trends in some cases, a statistical approach may be needed in others. While it is certainly beneficial to obtain as much data as possible, we don't believe that this will make the variability disappear. Any additional data will better enable one to determine the trends as well as a measure of the variability such as the standard deviation. The standard deviation can be important because the nature of these systems is that back to back tests with seemingly identical conditions can yield quite different results. Thus, it is possible in comparing cases that a lower mean extinguishment time for one set of system parameters may not necessarily be more attractive if its standard deviation is excessively larger than that for a second set of parameters.

III. OBJECTIVES

The specific objectives of the study were to: (1) compare the motion of charged and uncharged water mist droplets near a flame and (2) determine the reduced time for extinguishment due to electric charging of the water mist. This was to be accomplished in the context of element 4d of the Next-Generation Fire Suppression Technology Program, NGP, for new and more effective fire-suppression technologies that are presently conceptual. The proof of concept of the new technology has been demonstrated in the current program.

Our overall objective in the present program was to show that electric charging has a beneficial effect on improving fire extinguishment of pool fires. This would then provide the NGP program with the information needed to decide if additional funding should be appropriated for development of the charged mist concept.

IV. EXPERIMENTAL PROGRAM

A detailed description and discussion of the experiments is presented below so that reproducing the experimental conditions used in this work is possible. With the variability in results discussed above, such reproducibility is necessary to advance further understanding and development.

A. TEST CHAMBER

A fire test chamber shown in Fig. 2 was constructed after consultation with Mr. Alexander Maranghides of GEO-CENTERS, Inc. We also obtained useful ideas for the chamber construction from Prof. Constantine Polymeropoulos at Rutgers University [Downie and Polymeropoulos, 1995]. Our chamber has a steel frame, Lexan walls, and a metal flame hood at its top that leads to a duct flow booster exhaust fan. The chamber plan view dimensions are 1.2 m x 1.2 m, and the viewable height through the Lexan window is about 1.8 m. The bottom of the chamber is open with a vertical height of at least 0.3 m, around the periphery of the bottom of the chamber for fresh air to enter. A horizontal beam located about 0.5 m above the bottom of the side walls was used to mount all of the burners and fuel pans. A translating beam located 0.13 m above the fuel pan holds the water collection pans used to determine the water distribution. The translating beam is moved out of the way when fire extinguishment tests are performed. The booster fan was at its half point power position for all extinguishment tests. The chamber's metal structural elements, the flame hood, the spray nozzles, the water pipes, the fuel pans, and the water collection pans were all electrically grounded.

B. DROPLET MOTION DUE TO CHARGING

A major hypothesis of the program is that there is an attraction between the negatively charged droplets and the positively charged flame. The first step of our program was to verify that the droplets were being charged and to estimate the magnitude of the charging effect and the corresponding induced motion. Once this was established, tests were performed to detect additional motion of the charged droplets near the flame.

1. Estimates of Electric Charging and Field Effects

Initial tests were implemented to determine the electric forces on charged droplets in terms of their motion near a grounded metal screen.

a. Hollow Cone Nozzle

A Cone Jet TX - 1 hollow cone nozzle was chosen to observe the attraction of the charged mist to grounded objects and fires. We expected that the droplets dispersed in the hollow cone pattern would be easier to track compared to a solid cone spray nozzle. The characteristics of the TX - 1 are given in Table 2.

b. Positive Inductive Electrodes

Charging was produced by an inductive principle in which an electric field is established between a positively charged ring and three grounded wire tips in a pitchfork configuration formed by three soft copper wires that were twisted to form a single basic wire shaft (Fig. 3).

The positive ring induces electron emission from these grounded wires, and these electrons attach to the droplets. The process is aided by the fact that the electric field also aligns polarized droplets so that the positive ends of droplets point toward the grounded wires. The proximity of a positive end of a nearby droplet produces the extra field strength to remove electrons from the wire. From principles stated by Kelly [1994], the charges will distribute themselves among the available droplets.

This electrode configuration was typically operated between 5 to 15 kV with a Gamma High Voltage Research Inc. dc power supply. This power supply is small and light weight. It delivers 1 kV output for each 1 V input so that it can be operated with batteries or the low voltage dc normally found in fire control systems (typically 24 V). At 15 kV many droplets tended to head back toward the grounded nozzle body. Thus, the maximum effective spreading of the spray pattern occurred at around 10 kV.

c. Grounded Screen Tests

The metal screen was positioned vertically and displaced about 13 cm away from the nozzle centerline (Fig. 4). Applications of 5 to 15 kV with the Gamma High Voltage Research Inc. power supply to a positive inductive electrode showed that the droplets from the TX - 1 hollow cone nozzle were strongly attracted to the screen.

Moving the grounded electrodes as a whole to different locations in the spray, e.g., directly underneath the nozzle or off to the side, did not seem to make a big difference in the charging effect.

Because the droplets traveled nearly horizontally towards the screen, the electrostatic force on them due to their charge and the electric field generated by the bulk of the charged droplets greatly exceeded the net gravitational force on them.

d. Droplet Charge Estimates

We can get some idea about the amount of droplet charging by assuming that the ratio of the horizontal component of the droplet velocity to its vertical component is the same as the ratio of the droplet's horizontal electrical force to its gravitational force

$$F_{electrical}/F_{gravitational} = V_{horizontal}/V_{vertical} \tag{2}$$

This relation is valid if the droplet velocities are based on either of two extreme physical limits: (1) the two accelerating forces are equal to the corresponding component of the droplet drag force or (2) the drag is small compared to the accelerating forces.

The ratio of the forces is

$$F_{electrical}/F_{gravitational} = 3\ q_d\ E/(4\ \pi\ R_d^3\ \rho_d\ g) \tag{3}$$

where q_d is the electrical charge on a droplet, R_d is the droplet diameter, E is the electric field strength, ρ_d is the droplet density, and g is the gravitational acceleration.

An important characteristic droplet charge value is the Rayleigh limit droplet charge $q_{Rayleigh}$ [Bellan and Harstad, 1997] since the droplet will break up into smaller ones if this charge is exceeded. Here

$$q_{Rayleigh} = [64\ \varepsilon_o\ \sigma\ \pi^2\ R_d^3\ ]^{½} \tag{4}$$

where ε_o is the free space electrical permittivity constant and σ is the droplet's surface tension. For our case $q_{Rayleigh}$ is around 4 x 10^7 electrons per droplet. It is common practice to describe the actual droplet charge as a per cent of the Rayleigh limit charge. Thus, 1% of the Rayleigh limit still corresponds to 4 x 10^5 electrons.

The electric field is determined by the distribution of all the charged droplets and the positioning of the high voltage electrode and all the grounded surfaces. Since we don't know what the charge distribution is, it is not possible to determine E without making some important assumptions and additional computations. However, we can estimate the product of q_d E from Eq. (3) and, thus, compare some possible combinations of q_d and E.

Using Eq.(2) to describe the force ratio and writing q_d as a per cent of the Rayleigh limit value, the electric field vector in volts/meter is

$$E = 71{,}970\ (V_{vertical}\ /V_{horizontal})/\ (\%\ \text{of}\ q_{Rayleigh}\ ) \tag{5}$$

It is difficult to estimate the velocity ratio since it is so large, and it does vary at different locations. But, if it was arbitrarily equal to 100, and if the droplets were charged to 1% of the Rayleigh limit, then E = 7.197 x 10^6 V/m = 71,970 V/cm which is more than twice the breakdown voltage value for air of 30,000 V/cm. Thus, a droplet charging value of 3 to 4% (with a correspondingly lower value of E) would not be unreasonable. Gottuck et al [1993] estimate that the charging in their case was

4% for a spray with a similar droplet size. By rearranging Eq. (5) to solve for per cent of Rayleigh charge as a function of E, our estimate for the per cent charging increases if the electric field strength is lower and decreases if the velocity ratio is lower.

2. Attraction of Droplets to Flames

Tests were performed with the same positive inductive electrode and TX - 1 hollow cone nozzle with flames positioned off to the side of the nozzle centerline instead of a metal screen. First, a small propane diffusion flame was positioned a little over 0.30 m from the centerline of the nozzle (Fig.5a). Application of a 15 kV voltage made the droplet trajectories transition from a vertically downward direction to a nearly horizontal orientation directed towards the base of the diffusion flame (Fig.5b).

Similar tests were instituted for pool fires in a 9 cm diameter pan using heptane in one case and methanol in a second. While there was a noticeable increase in the spray angle due to charging, the trajectories did not display the large horizontal motion observed for the propane diffusion flame and appeared to be more continuously vertical near the fire. Charging seemed to increase the amount of water reaching the pool fire, but this may be due to the effect of self-repulsion which would increase the diameter of the region covered by the spray.

There are indeed be differences between the gas diffusion and pool flames. The heptane flame produces more soot particles which can attach electrons after the particles cool. The methanol flame is not expected to produce chemiions.

Estimates can be made for the electric field and charging using the velocity ratio in Eq. (5), typically on the order of 0.5. If the charging level is the same as in the case of attraction to a metal ground, then the electric field will be on the order of a hundred times weaker relative to the estimates we made in the previous section. In making these estimates, one should be aware that air currents, which we have not accounted for, will also have an effect on the velocity components.

More work is clearly needed to understand these observations, and this work is justified based on the indications to be discussed below that charged mists are more effective than uncharged mists for fire extinguishment.

C. FIRE EXTINGUISHMENT TESTS

Our program focused on presenting results in a form similar to those of Patterson et al [1996] as discussed in the literature review. They obtained fire extinguishment time as a function of the water flux in an unventilated chamber. We planned to obtain extinguishment time as a function of water flux with and without electric charging for a different nozzle and nozzle arrangement, a different size fire, and a different chamber. The fire extinguishment study by Gottuck et al [1993] in an open environment pointed out the importance of charging in changing the water flux. For this reason, almost all measurements of extinguishment time, both with and without charging, were either immediately preceded or followed by a measurement of the water collected at the location of the fuel pool pan.

We were advised by NRL to try to achieve a uniform spray pattern whose diameter was 10 times that of the fuel pan. In accordance with this, a 10 cm diameter fuel pan (the same size as that of Gottuck et al) was chosen to study turbulent fires since, according Babrauskas [19], the range from 5 to 20 cm produced a convective, turbulent burning mode. The next range from 20 cm to 1 m corresponds to a radiative, optically thin burning mode, and the radiative optically thick burning mode corresponds to diameters greater than 1 m. If we had chosen to study fires greater than 10 cm, then we would need at least a 20 cm diameter fire to get into the next range of flame structure. To plan for a 10:1 chamber to fire diameter ratio would mean chamber floor dimensions in excess of 2 m, and this was not feasible under this program.

The 5 cm fire (actually 4.9 cm, and smaller than the 5.08 cm fire studied by Patterson et al, 1996) that we also studied is on the borderline between laminar and turbulent conditions. Most of our flame appears laminar, but there is some flickering at the tip.

1. Ten Centimeter Diameter Pool Fire

a. 7N Spray Nozzle System

Much effort was needed to develop a spray system that would provide a uniform distribution of water over a diameter of 1 meter, ten times the diameter of the 10 cm dia fuel pans we were to use. A special consideration was that droplets carrying the same sign of electrical charge will tend to repel each other. The effect of the self-repulsion would be to produce spreading of the droplets and reduce the water flow per unit area.

The idea of using an array of 7 to 8 individual nozzles to form a uniform spray (following the guidelines of Patterson et al [1996]) was briefly considered. In order to do this, we would have first had to find the proper nozzle spacing and flow rates to form a uniform spray and extinguish a pool fire without electrical charging, and then repeat the process with charging. This would almost certainly have required changing each of the nozzle's flow rates and possibly their spacing to maintain the same uniform water spray flow rate per unit area when the droplets were charged. Nozzle replacement was needed in the experiments at NMERI. The process of constantly changing the plumbing and checking for spray uniformity was not feasible within the limited resources of our program.

We decided to use a single nozzle assembly called the 7N, recommended by Spraying Systems, Inc., which holds 7 individual hollow cone nozzles (Fig.6). The 7N assembly has a single 1" water pipe connection which feeds one central nozzle and six outer nozzles at a constant radius from the center one. The axes of the outer nozzles are canted away from the centerline. Spraying Systems, Inc.

asserts that the droplets from the individual nozzles cross paths so that a somewhat uniform spray is produced. They do not have specific quantitative measurements to confirm this.

Droplet size information is available for pressures greater than 100 psi with relatively small changes in droplet size occurring at higher pressures. Although the individual nozzles are rated for very high pressures, the supplier said that the nozzle holder is rated only up to 150 psi. We later spoke to Robert Darwin, Director, Fire Protection Division, NAVSEA, who has used the 7N at pressures of over 1000 psi [Darwin, 1997]. We told our local Spraying Systems representative about this, but he still held to the 150 psi limit. We followed the Spraying Systems guidelines so that our operating range was limited to between 100 and 150 psi.

A water feed system was designed and assembled with the water pressurized by nitrogen from a regulated high pressure cylinder to cover the range of pressures to be used with the 7N nozzles.

We expected that different sized nozzles might be needed to cover the range of conditions for our tests. Based on a preliminary test of fire extinguishment with a single nozzle, 1.5 gph nozzles were selected for the 7N with the assistance of the Spraying Systems, Inc. representative. Our plan was to install the 7N assembly with 1.5 gph nozzles, observe its fire extinguishment performance with and without charging, and purchase one or more additional 7N assemblies with the appropriate flow capacity nozzles to cover our range of testing. (Note that it is less expensive to purchase an entire assembly than to purchase the 7 individual nozzles!) Thus, in all cases the overall geometry would remain unchanged whether or not the droplets were electrically charged or the water flow rates were to be changed by replacement of the 7N assembly or individual nozzles. The water flow per unit area would be controlled by varying the water pressure and changing the nozzles. There is little change in droplet diameter in going up or down one size in nozzle flow capacity.

Since extinguishment times with the 1.5 gph nozzles were found to be short, a lower capacity 7N supplied with seven 1 gph nozzles was obtained to cover the range of lower flow rates and longer extinguishment times. The characteristics of the 7N system with 1.5 gph nozzles is given in Table 3 and those of the 1 gph 7N system are given in Table 4.

b. Electron Emission Electrode

Charging the spray from the 7N nozzles was challenging because of the close proximity of the nozzles to each other. In a more typical setting in which water was supplied separately to a number of individual nozzles, rather than an assembly, it would be relatively easy to assure that the droplets from each nozzle were charged using an individual charging electrode. For the 7N we decided to position a single circular large diameter charging electrode coaxially around the 7N assembly.

A 3.8 cm wide strip of wire screening material was rolled into a circular hoop and fastened on the inside of an 0.2 m diameter ring made of copper tubing (Fig. 7). The orientation of the screening material was vertical. We hoped that this would decrease water collection on the screening and large droplet formation. This strip produced electron emission from both the top and bottom rows.

The cut screen mesh provided approximately 250 sharp points on the top and the same number on the bottom of the electrode to charge the droplets from the outer set of six nozzles with the 7N grounded. The question was if the center nozzle mist would become charged. Our rationale on this issue was that since the outer and central nozzle sprays cross over according to Spraying Systems, some charged outer nozzle spray would find its way to the center of the system and some inner nozzle spray would move out and become charged due to its proximity to the charged outer nozzle droplets. Also, earlier tests using the inductive approach with grounded wires as the electron source indicated that the ability to charge droplets was not strongly linked to the position of those electrodes.

One might think of an individual multiply charged droplet near an uncharged droplet as an inductive source of electrons in the sense of the inductive wire electrodes. Thus, an uncharged droplet will become polarized when it passes close to a charged droplet. The positive end of a polarized droplet will become aligned with the negatively charged droplet. The additional electric field strength associated with this alignment will result in the transfer of electrons from the charged to the uncharged droplet. In this way we hypothesized that a cascade effect could transfer electrons from regions of charged to regions of uncharged droplets.

Despite our precautions some large drops formed on the strip electrode and dripped off, but they did not fall into the fuel pan and thus did not affect fire extinguishment. These larger drops are less susceptible to the effects of air flows induced by the ventilation fan or the fire plume. In a more realistic environment with individual chargers for each nozzle, dripping would not be expected to be important.

c. Water Flow Distribution

Water flux uniformity tests were made using nine 10 cm diameter pans to collect the water (these were identical to the pan used to hold the fuel for the pool fire). These were placed side by side on a beam that could be slid on a rail into position above the fuel pan, and then be moved easily out of the way when fire extinguishment tests were performed. This array of collection pans was about 13 cm above the plane of the fuel pan, and the entire array of pans spanned a distance of 0.9 m.

With all seven of the 1.5 gph nozzles installed in the 7N, the flow was quite peaked with its maximum off slightly from the centerline of the nozzle (Fig. 8). Note that Spraying Systems, Inc. asserts that the spray is uniform over a diameter of 0.75 m if the assembly is more than 0.9 m above the collection plane. Thus, the assembly did not operate as anticipated. It is unclear whether this pattern is characteristic of all 7N assemblies or whether it was influenced by the particular chamber in which it was installed.

When the 0.2 m dia multiple nozzle design electrode ring was placed around the nozzle, the spray pattern appeared to be more symmetric, but was still peaked. Dripping from the electrode contributed significantly to the water collected on either side of the main peak at ± 10 cm from the centerline. While these drops do have a major effect on the water collection, they do not appear to play any significant role relative to fire extinguishment because the water they carry does not interact with the fire and does not splash the fuel surface.

Plugging the center nozzle produced a fairly uniform water flow distribution. In this case the spray patterns of the 6 remaining nozzles appeared to project further out radially so that the walls of the chamber became wet at a greater height above floor than had been experienced before. It thus appeared that the central nozzle played an important role in determining the spray patterns of the other six nozzles. Possibly, air entrained by the central nozzle affected the air flow environment that the other nozzle sprays experienced. Unfortunately, the water flux without the center nozzle flow was too small to extinguish the fire being studied.

For this reason, we compromised and replaced the center nozzle with a 1 gph capacity nozzle and retained the six other 1.5 gph orifices in the 7N assembly. This did not produce any dramatic change in the water distribution (Fig. 8), but it did allow us to set a pressure that would provide extinguishment times in a good range for our measurements.

The water flux distribution of the 7N nozzles with the 1 gph center nozzle is shown in Fig. 9 when the electrode is uncharged and at -5kV. Charging reduces the center water flux and increases that at the edges of the spray pattern slightly. These changes are much less than those observed by Gottuck et al [1993] for a single nozzle. In the case of the 7N nozzles, charging of the outer portion of the spray makes those droplets spread out in all directions, and the outer spray droplet charge density restricts the spread of the inner charged spray.

d. <u>Ten Cm Diameter Pool Fire Extinguishment Tests</u>

Experiments to determine the effect of mist droplet charging on the extinguishment of a heptane pool fire were performed in the test chamber. The water spray system consisted of an electrically grounded Spraying Systems, Inc. 7N nozzle containing a central 1 gph nozzle and six circumferential 1.5 gph nozzles located 1.1 m above the pool fire. A 0.2 m diameter electron emission charging electrode, described previously, was placed coaxially around the water spray system centerline and located about 10 cm below the bottom of the nozzle assembly.

Heptane was poured into a 10 cm diameter, 2.8 cm tall seamless and electrically grounded tin pan until the fuel level was 0.8 cm from the open end. The fuel was ignited and the fire continued for 3 minutes to develop a steady state structure. Water flow at pressures between 100 and 150 psi was supplied to the 7N nozzles immediately following the initial heating period. Measurements of extinguishment time were made separately both with and without dc electric field charging of the mist. Water flow measurements were made both with and without dc electric field mist charging by replacing the fuel pan with a water pan of the same size as the fuel pan and the nine pans used previously for water distribution measurements.

Because some previous tests had found large effects with low voltage charging, the tests reported began with voltages on the order of -1 and -2 kV at 150 psi. Measurements were then continued at -5 kV at this pressure as well as at pressures of 100 and 125 psi.

Frequent water flow measurements were needed since it was clear that the water flux at a fixed nozzle pressure varied. These variations develop due to changing air flow patterns in the chamber or deposits found in the nozzle in spite of the use of a 2 μm filter in the water line.

Extinguishment time is plotted in Fig. 10 as a function of water flux with and without electric charging. Because the voltage level at 150 psi did not produce a clear trend for values between -1 and -5 kV, all of the charged mist data is plotted together for these experiments. The voltage was maintained at -5 kV for all the other droplet charging cases. At the higher flow rates, it does not appear that there is a definite effect of electric charging. However, electric charging does produce major improvements over the performance of uncharged droplets in the lower water flux range. As the flux is lowered without charging, a flow rate is reached where significantly greater times are needed to extinguish the fire. It is in this range that electric charging prevents extinguishment time from growing significantly as it does in the uncharged case. The curves can be interpreted as showing a decreased extinguishment time at constant water flux or reduced water flux to achieve a given extinguishment time. This behavior would beneficial in cases where the water supply for fire extinguishment is limited. We suspect that the extinguishment time with charging would also increase if the water flux were lowered much more. Data was not taken for smaller fluxes with this nozzle because the water collection values were inconsistent for pressures below 100 psi.

The nozzle and electrode were removed and cleaned and then reinstalled after the above initial set of data had been analyzed to obtain a second set of data. In the new tests, the water collected in the single pan directly below the nozzle increased due to charging, which was different from our other observations including the previously mentioned water flux distribution measurements recorded in Fig. 9. In the spirit of the random data obtained by Patterson et al [1996] we added these new data points to those previously displayed in Fig. 10, and the total data set is presented in Fig. 11. The trend of rapidly growing extinguishment time with decreasing water flux is not as apparent for the uncharged case as in Fig. 10. For this reason linear fits to both the charged and uncharged data sets were made and are displayed in Fig. 11. Again, there is little difference in extinguishment time due to charging when that time is generally small at the higher water flux rates, but the uncharged case still has extinguishment times that are significantly higher, by a factor of nearly 2, than the charged case in the low water flux regime where extinguishment times are larger. The standard deviation of the uncharged data is nearly twice that of the charged results. Thus, the complete set of data still shows a clear improvement in extinguishment due to charging even though we have some suspicions about the validity of the additional data because of the higher water collection.

2. Five Centimeter Diameter Pool Fire

Because of difficulties in holding the 7N nozzle water flow rate constant in the water collection pan and the possibility that the center nozzle mist might not be receiving as much charging as the outer nozzle mist, we decided to perform additional work with a single water mist nozzle and a smaller, 5 cm diameter, fuel pan. More repeatable water collection rates and more effective charging of the mist were expected with the single nozzle. The smaller fuel pan was chosen to maintain the ratio of the spray diameter to the pan diameter much larger than unity.

a. Solid Cone Nozzle

The lowest flow solid cone Spraying Systems, Inc. nozzle is the TG - 0.3 whose flow characteristics are given in Table 5. Spraying Systems does not state a coverage area for the TG - 0.3 nozzle, and insufficient time and funding were available for specific water flow distribution measurements in this work. However, the spray visually appeared to be relatively uniform over a diameter of 0.25 to 0.30 m at a distance of 0.7 m from the nozzle. Based on this observation, the ratio of the spray diameter to pan diameter was between 5 and 6.

b. Single Nozzle Electron Emission Electrode

A new electrode for these tests consisted of a wire screen with a 8.9 cm diameter circle cut out of its center. The cut inside edges of the screen formed the array of wires that emit electrons (Fig. 12). This screen was positioned horizontally with its center point being coincident with the spray nozzle centerline. It was secured to the circular ring electrode that had been used in the positive inductive electrode system discussed previously (Fig. 3). With the nozzle grounded, an easily visible spreading of the spray pattern was observed with the application of -3 kV. This spreading was increased considerably when the voltage was increased to the maximum value of -5 kV of a Bertan power supply.

c. Five Cm. Diameter Pool Fire Extinguishment

Heptane was poured into a 5 cm diameter, 1.6 cm tall seamless and electrically grounded tin pan until the fuel was 0.6 cm from the open end (this is almost the same diameter as used in the study of Patterson et al [1996]). The fuel was ignited and the fire was allowed to stabilize for 1 minute. Water flow at pressures between 30 and 60 psi was supplied to the TG - 03 nozzle immediately following the preheat period. Measurements of extinguishment time were made separately both with and without dc electric field charging of the mist. In most cases the extinguishment time measurements were followed by water flux measurements in a separate 5 cm dia pan that was identical with the fuel pan and was placed in the holder that supported the fuel pan.

The distance between the nozzle and the fuel pan was set as 0.7 m. Extinguishment time was then measured as a function of the water flux collected in the 5 cm diameter pan at zero voltage and at -5kV.

When the electrode was charged, there was a considerable decrease in the water flux collected in the pan because of mist spreading. Thus, the nozzle was operated at a higher pressure when charging was applied to obtain the same range of collected water flux rates that had been obtained at lower pressures without charging.

The results plotted in Fig. 13 show that the expected rise in extinguishment time for the charged case occurs at a lower level of water flux than for the uncharged case. The solid line is a linear fit of the three water flux points for the charged case. A dashed line with the same slope is shifted to the right of the solid line to indicate the general upward trend for the uncharged case. This confirms the general trend seen for the 10 cm diameter fuel pan fire which also found improved extinguishment with charging. As we noted for the 10 cm case the extinguishment times are significantly shorter with charging for the low water flux range in which the uncharged extinguishment times began to grow.

V. <u>DISCUSSION OF RESULTS</u>

The present results are compared with other data obtained at NMERI by Patterson et al [1996] and at Hughes Associates, Inc. by Gottuck et al [1993]. The fitted curve results of Patterson et al [1996], the fitted data shown in Fig. 11, and the trend lines in Fig. 13 are plotted together in Fig. 14. The curves in Fig. 11 are rather than those of Fig. 12 because the 10 cm pan uncharged data falls more naturally between the NMERI data and the AeroChem 5 cm pan data and the additional water flux data included in Fig. 12 was inconsistent with our other tests. The experiments of Gottuck et al [1993] occurred for water flux rates that were more than twice those treated in our experiments and thus outside of the range of Fig. 14. Although Patterson et al [1996] did not consider charging, the NMERI data shows the general feature of the rise in extinguishment time as water flux is reduced beyond some point and substantiates the present observations of a rapid rise in extinguishment time for the case without charging. Note that the high water flux measurement region (small extinguishment time) of our curves closely follow the data of Patterson et al [1996]. Although they were careful to establish uniform water flux, and they do not have additional air motion due to ventilation, their extinguishment time data is at least as variable as the present data. Although, the apparent randomness appears to be inherent to this kind of problem, it does appear that the water flux is a rational basis for comparing and interpreting extinguishment results when using water mists.

Even though Gottuck et al [1993] treated a larger 10 cm dia. fire, our 5 cm dia. pool fire test was performed with the anticipation that our results might be related to theirs because we both used a single spray nozzle. Although the ranges of water flux for these two cases do not coincide, the steep slope of the curves in Fig. 13, replotted in Fig. 14 , that we observed for the smaller diameter fire is consistent with their statistical description of fire extinguishment. If we had set an arbitrary time standard for the definition of fire extinguishment within finite regions of water flux, the randomness of our data would have also resulted in a statistical description with the per cent of extinguishment decreasing as water flux is decreased, as seen in the Gottuck et al [1993] results.

We also found that charging the mist reduced the water flow directly under the single TG - 0.3 nozzle to around 75% of its value without charging. The data of Gottuck et al [1993] shows a reduction to around 85%. For the multiple nozzle configuration, the reduction of the water flux directly below the nozzle assembly was much smaller, being about 95% of the uncharged value. In addition, the increases due to charging at large distances were also small as seen in Fig. 9.

Two possible reasons for the small reduction in water flux below the nozzle assembly compared to the single nozzle case are that: (1) the repulsive forces due to charged droplets at larger diameters restrained the tendency of the smaller droplets to spread and (2) an insufficient amount of charge was available to the multiple nozzle spray, and in particular the central portion of the spray, to grossly affect its geometry. This is not a major concern, as it simply indicates the need for a more effective charging electrode for the 7N nozzle.

Thus, we confirm the conclusion of Gottuck et al [1993] that charging will produce a large amount of spreading in the mist distribution for single nozzles. It is clear that charging applied to an array of single nozzles will enable one to use greater spacing between the nozzles while achieving as uniform a spray pattern as in the case without charging. This is of particular concern for small droplets which are hard to disperse transversely due to their high aerodynamic drag. The electrostatic forces help to spread them out more evenly.

The data from three different organizations span very different water fluxes because the physical conditions are significantly different, and this should not be a significant consideration in our overall comparison. The NMERI data was collected in a chamber with a very smooth water flux distribution and no ventilation. The AeroChem data was collected in a chamber with a more peaked water flux distribution and a finite amount of ventilation. The Hughes data was collected in the open with a water flux distribution that was more peaked than in the AeroChem 10 m cm pan test and probably around the same as in the AeroChem 5 cm pan test. The water flux needed to get into the critical range for which extinguishment time becomes strongly dependent on flux probably depends more on the chamber conditions and the type of fire.

It is obvious that extinguishment depends on the interaction of a number of complex mechanisms. If the system enters one mode of operation or reaches some evolutionary stage, it can than increase or decrease the effectiveness of particular extinguishment mechanisms as the following indicates..

In this work the system consisted of a small turbulent pool fire sitting well above the floor in a ventilated chamber. When there was sufficient water flux to extinguish the fire in some finite amount of time, the flame appeared to resemble open flower petals rather than the vertical column of a classical undisturbed diffusion flame. The flame would fluctuate between this case and one which looked a little more like a classical flame.

The clear questions are: (1) What is the flow pattern produced by the buoyancy in this case? (2) Might it be that this spread position with a larger horizontal flame area actually heats up more gas and increases the extent of the buoyant plume? The plume is then able to reduce the amount of mist that can reach the flame's stabilization point so that it can then reform back into a more classical flame. But when that happens, more mist can approach the stabilization points and the flame bends back over. A fire may pass through a number of cycles like this before extinguishing. If this is a general way for pool fires to extinguish, then understanding how this process works can improve our ability to extinguish fires both with and without charging.

The spread flame position is consistent with a stagnation point located above the fuel pan. Indeed it is common for counterflow diffusion flames to first experience quenching in the center of the flame where strain rates are the highest. This corresponds to the absence of flame above the center of the fuel pan in our tests. Thus, a counterflow diffusion flame experiment would provide a good fire simulation. A variation of this would be a gas diffusion flame pointed down with a water mist spray directed upward at it. This would eliminate any problems with dripping and focus on extinguishment without considerations of vaporization of a gaseous fuel.

The present results clearly show that application of negative charging to water mist reduces the extinguishment time when the water flux is at its lowest effective values. Within this range the water flux needed to attain a given extinguishment time is also reduced. This is true for both the 5 and 10 cm heptane fuel fires and two different nozzle and charging systems. For the 10 cm fire data in Fig. 11 the variability in extinguishment time, expressed as the standard deviation, was reduced at low values of water flux.

The question of the effect of charging on the total amount of water, Q, per unit floor area needed to extinguish a fire requires some further discussion. Q is equal to the product of the water flux, f, and the extinguishment time T so that

$$Q = f\,T \tag{6}$$

and it has the dimensions of a length (or thickness). Patterson et al [1996] refer to Q as the "de novo thickness."

Ways in which reductions in Q can be categorized include: (1) a reduction in the flux, f, at constant extinguishment time, T, (2) a reduction in the time, T, at a constant value of flux, f, and (3) an absolute maximum reduction of Q for some combination of T and f. The first two cases are readily seen by comparing curves with and without charging in Fig. 14 for either fixed f or T.

To better understand the condition for an absolute maximum reduction in Q note that the case of constant Q from Eq.(6) corresponds to

$$T = Q / f \tag{7}$$

so that in a plot of extinguishment time vs water flux, $T \to \infty$ as $f \to 0$ and $T \to 0$ as $f \to \infty$. Since the NMERI data in Fig. 14 remains finite as $f \to 0$, this data actually shows a trend of decreasing Q for small f, although the absolute minimum Q occurs for an intermediate value of f close to 1.5 L/min-m^2. The fitted curve of the NMERI data corresponds to increasing values of Q for large f since T levels out in that range.

For the AeroChem data in the case of no charging, T appears to grow without limit in Fig. 14 for both the 5 and 10 cm fires for finite f so that Q will become infinite as f decreases. Charging allows a much smaller flux f of water to be used to achieve extinguishment in the same time. Here the reduction in Q due to charging can be accomplished in a limited range of f at the same T (Fig. 14). For the 10 cm case there is insufficient data to make any statement about how small a value of f can be used to minimize Q.

Gottuck et al [1993] argue that one can simply increase the flux f to achieve the same effect as charging. This may be a simple alternative in the single nozzle, well ventilated case, but there are broader ranges of f in different problems over which electric charging has a beneficial effect. Increasing f (without significant reductions in extinguishment time) is the wrong approach in a Halon replacement program to minimize the weight of the fire suppressant. Work there should focus on increasing the effectiveness of the technique so that smaller values of f will be capable of extinguishing a fire.

Although the effects of ventilation and uniformity cannot be fully separated, a shift appears to be occurring in our tests relative to the Hughes Associates, Inc. data to move the extinguishment time curves to lower water flux values and to reduce the magnitude of their slope. Because of this we anticipate that conditions such as those reported in Fig.1 for unventilated chambers and highly uniform water flux will yield significant reductions in extinguishment time T when charging is applied. In that case T would be greatly reduced for low f so that Q could be reduced both in the absolute case and for the same extinguishment time according to Eq. (6).

The practical application of charged water mist will at some point involve its economics. The major cost for a charged mist system is the high voltage power supply. If a low voltage (24 V) dc power supply, such as is normally found in fire control systems, is available, than a simple, small, solid state device can be used. For voltages under 10 kV prices are less than $200 for a device that could charge several electrodes. A higher current, high voltage unit that could handle more electrodes would be more economical for a large scale system. Less expensive power supplies are used for TV electron guns, but some developmental work would be needed for our application.

Although we have not settled on a single type of electrode, the materials used for an electrode are generally quite inexpensive. This cost can be balanced against potential savings due to the increased spray angle with charging. These savings arise due to a smaller number of nozzles, fittings, and a shorter overall pipe length.

VI. TECHNICAL PROBLEMS

The major technical problem was attaining a uniform water flux distribution and maintaining the rate achieved from run to run. We don't know to what extent variation of the water flow at the same water pressure may have caused errors in our relation for extinguishment time as a function of water flux. However, the variations in extinguishment times observed in this work are the same as encountered by Patterson et al [1996] in the case of an extremely uniform water flux. It appears that the conditions used here achieved better control than the experiments of Gottuck et al [1993] since we find a more continuous distribution of extinguishment times. This may in part be due to our tests being performed in a chamber and with a smaller pool fire.

The problem of attaining a uniform water flux distribution was compounded by the need to do so for the two physically different cases of uncharged and charged water mist. We believe that much more uniform distributions can be achieved either by operating the 7N nozzle assembly with the center nozzle plugged and larger nozzles for the remaining 6, or installing an array of individual nozzles similar to those of Patterson et al [1996].

VII. RECOMMENDATIONS FOR ADDITIONAL OR ALLIED AREAS OF RESEARCH

Beneficial effects for the use of charging with water mists has been shown and that additional work in this area is warranted. The data show that fire extinguishment times can be nearly halved for cases where the water flux is low. It may be possible to decrease the extinguishment times for low water flux and also decrease it for higher water flux rates if the charging techniques can be made more effective.

While the objective of extinguishing a fire more rapidly or with less water is certainly of prime importance, the means of achieving that goal is of high importance in the long run. A greater emphasis is needed on more fundamental studies of fire extinguishment using both uncharged and charged mist in order to improve the technique. For example, the fact that extinguishment times at large water flux are comparable for the Hughes Associates Inc., NMERI, and AeroChem tests, yet differ substantially for low flux, suggests that ventilation does not play a role at high flux but does at low flux. If that is the case, then perhaps oxygen displacement is more important as a fire extinguishment mechanism than is cooling at low water flux.

Since the AeroChem charged mist results benefited from reduced ventilation relative to the Hughes experiment, we postulate that charging may be particularly beneficial for the mechanism of oxygen displacement. Droplet charging tests in a nonventilated chamber would help to test this hypothesis. In practical terms, it might suggest that limited flow charged mist systems are more effective in closed compartments than in large open spaces.

Although this discussion has focused on the particular environments of the AeroChem and NMERI test chambers, a more fundamental examination is needed of how charging of water droplets could be used to enhance extinguishment of a fire by the nonuniform spray of a single water nozzle in an open environment. It seems unlikely that a single nozzle spraying from above a fire in an open environment can provide much useful information for compartment fires. Such tests in the open would appear to be more useful with the water stream directed at angles typical of a portable fire extinguisher or a fire hose.

The observation that extinguishment of a pool fire by mist produces flame shapes consistent with a counterflow model was discussed above. For this reason future studies should also consider counterflow diffusion flames [Williams et al, 1997]. The counterflow flame can be set up with a gaseous fuel, and this will reduce some of the variability that may be present in the more complex case of a liquid fuel requiring a vaporization step.

Other work [Chaiken and Smith, 1998] has identified two modes of fire extinguishment dependent on whether the mist droplets are transported to a pool fire from above or from the side. Counterflow flames would treat the first transport mechanism and cup burners [Sheinson and Maranghides, 1997] could provide information on the second transport mechanism using liquid fuels.

An area related to fire suppression is smoke suppression. We believe that mist can be beneficial in reducing the smoke concentration. AARI has been successful in suppressing smoke using purely electrostatic fields and removing small particles from the air using a charged water mist. Much of the equipment that would be needed for smoke suppression studies has already been acquired for the current fire extinguishment program.

VIII. CONCLUSIONS

We conclude that there is a definite benefit in electrically charging water mist to extinguish fires. This has been demonstrated in experiments on small turbulent pool fires with extinguishment time and its standard deviation being reduced by a factor of nearly two. More work needs to be done to understand the basic mechanisms in order to speed progress in improving and optimizing the procedure over a wide range of conditions. While the present program has been limited to water mists, the same principles apply to any aerosol that might normally be useful for extinguishing a fire in the absence of charging.

An additional benefit that may arise from the use of electrically charged water mists is that the overall transverse dispersion of the mist can be increased. Normally, extremely high pressures or many nozzles would be needed to achieve sufficient coverage for a water mist sprinkler system.

The present program has focused on charging of mist from ceiling sprinkler systems, but it can also be applied to other situations such as extinguishing fires in aircraft nacelles or mobile units fighting fires with water hoses.

Similar mist charging systems have been used safely for dust suppression with no ill effects experienced by personnel standing in the charged spray. Mist charging thus appears to be safe for fire extinguishment applications.

IX. ACKNOWLEDGMENTS

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	Water Application Rate (L/min-square meter)		
	5.0 - 5.9	6.0 - 6.4	6.5 - 7.0
Uncharged (0)	0/0	6/13 (46%)	9/10
+ Charged	0/3	2/6 (33%)	0/3
- Charged	0/9	3/4 (75%)	0/0

Table 1 Demonstration of Effectiveness of Negatively Charged Mist.
Per cent of successful pool fire extinguishments shown.
Data of Gottuck et al [1993] of Hughes Assoc., Inc
.

TX - 1 Hollow Cone Nozzle				
pressure, psig	30	40	50	60
mean volume diameter, µm	108	101	97	93
flow rate, gph	0.89	1	na	1.5
total spray angle, degrees	na	54	na	na

7N - 1.5 Seven Hollow Cone Nozzle Assembly			
pressure, psig	100	125	150
mean volume diameter, µm	69	62	59
flow rate, gph	16.8	18.6	20.4
spray coverage diameter, ft	2.5	2.5	2.5

Table 2 Hollow Cone Nozzle Characteristics

7N - 1 Seven Hollow Cone Nozzle Assembly			
pressure, psig	100	125	150
mean volume diameter, µm	59	57	55
flow rate, gph	10.8	12.6	13.8
spray coverage diameter, ft	2	2	2

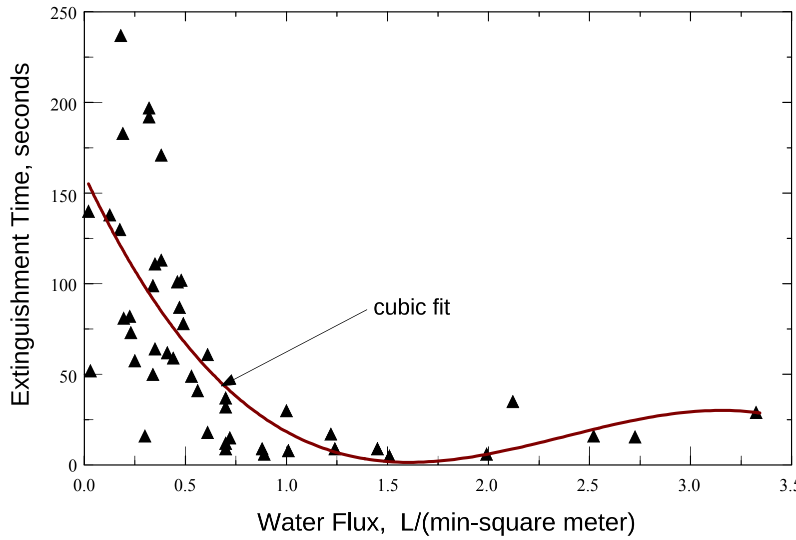
Table 3 Higher Flow Capacity Seven Nozzle Assembly

TG - 0.3 Solid Cone Nozzle				
pressure, psig	30	40	50	60
mean volume diameter, µm	250	210	180	160
flow rate, gph	3.1	3.7	na	4.4
total spray angle, degrees	51	54	na	59

Table 4 Lower Flow Capacity Seven Nozzle Assembly

Table 5 Solid Cone Nozzle Characteristics

TP-568



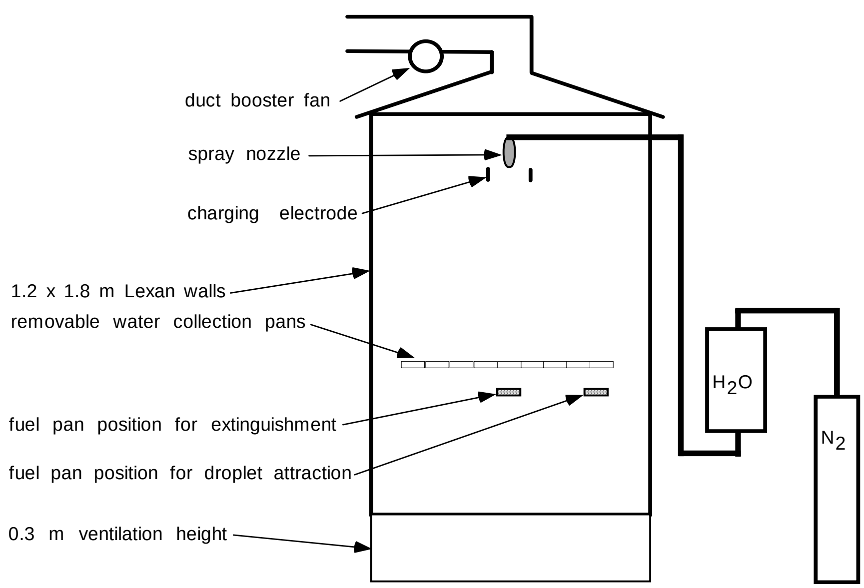


Figure 1 Extinguishment Data obtained at NMERI by Patterson et al [1996]
No electrical charging
5.08 cm diameter heptane pool fire

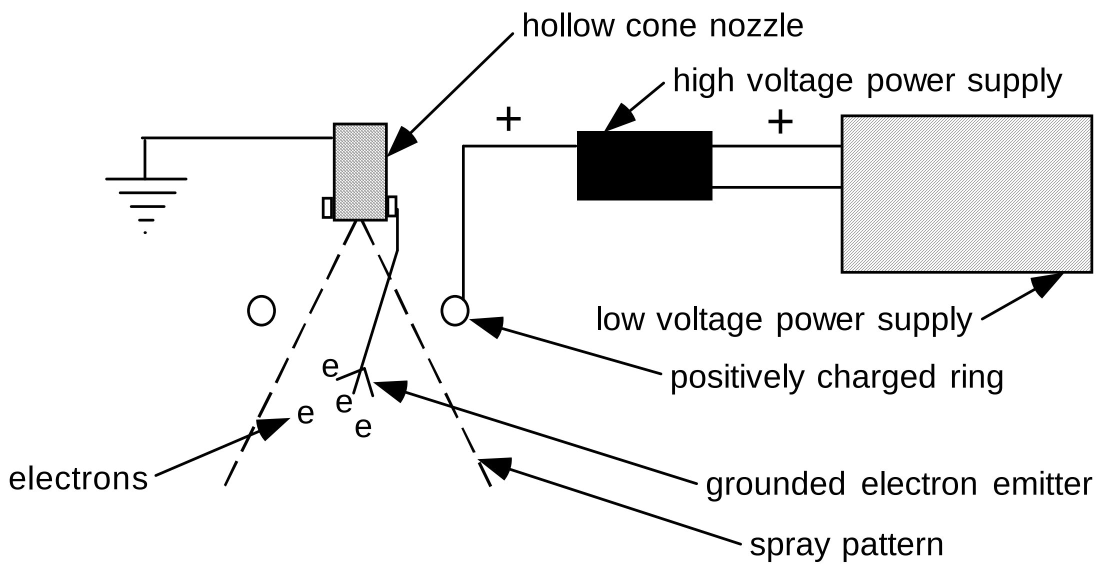


Figure 2 Schematic Sketch of Fire Test Chamber
Metal chamber structure, water nozzle, fuel pan, and water collection pans are all electrically grounded

Figure 3 Electron Induction Electrode

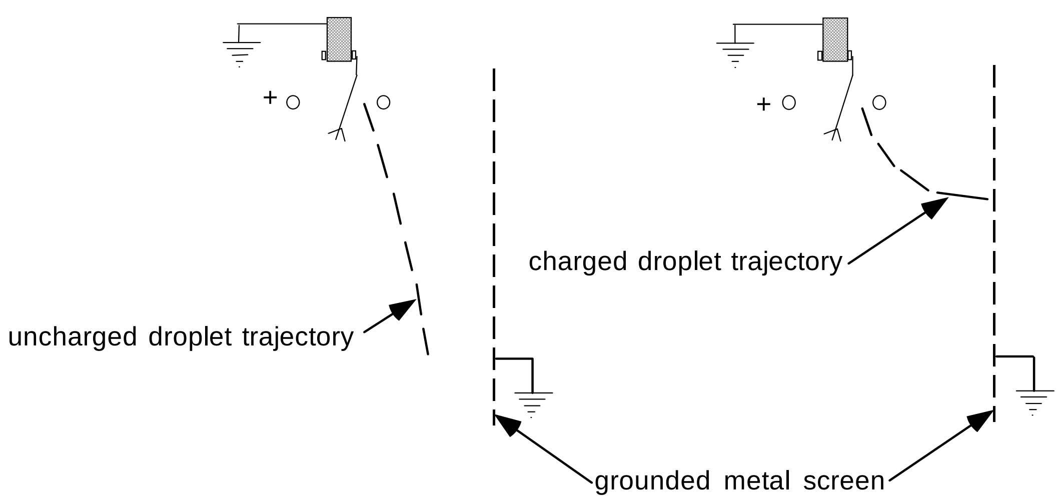
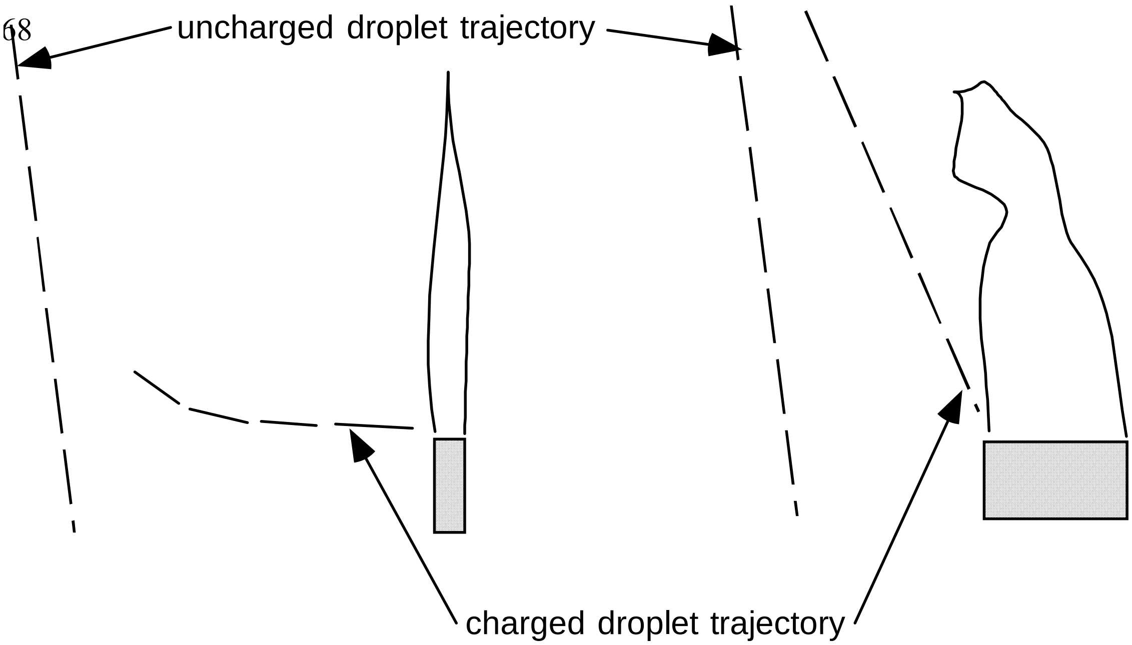


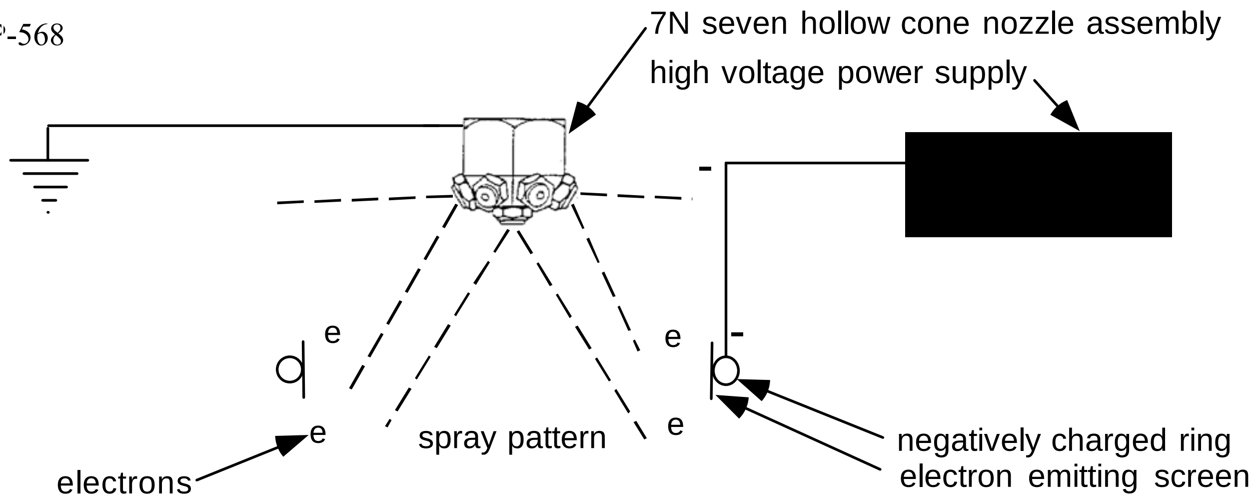
Figure 4 Attraction of Charged Droplets to Grounded Metal Screen



a. Propane flame

b. Heptane fire

Figure 5 Motion of Charged Droplets Near Fires



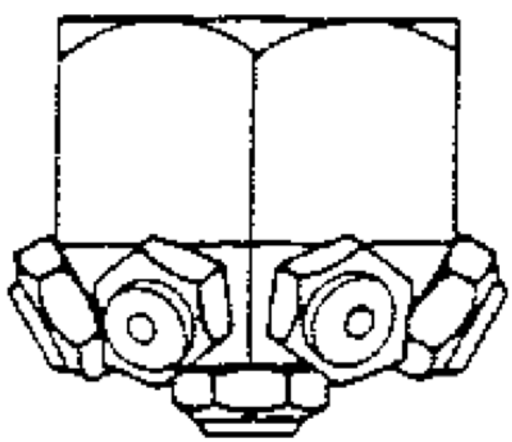


Figure 6 Spraying Systems, Inc. 7N Hollow Cone Nozzle

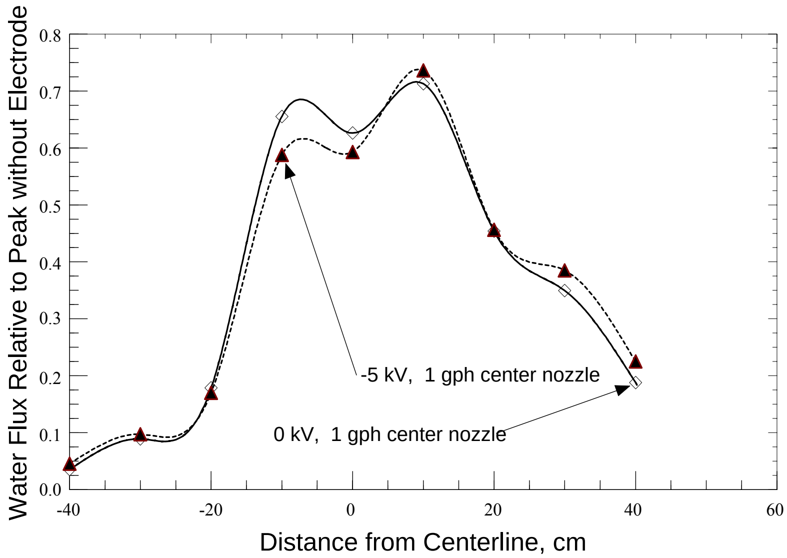


Figure 7Multiple Noz

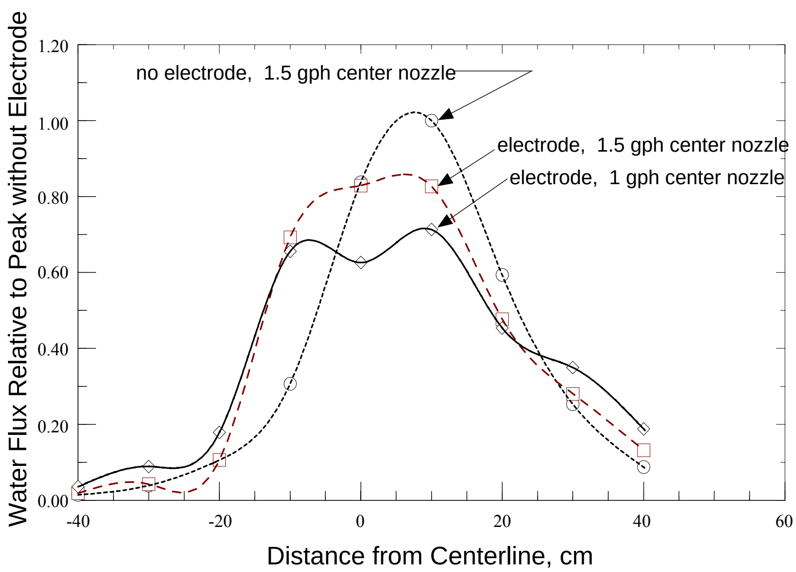


Figure 8 Effect of Center Nozzle Size on 7N Water Flux

Figure 9 Effect of Electrical Charging on 7N Water Flux

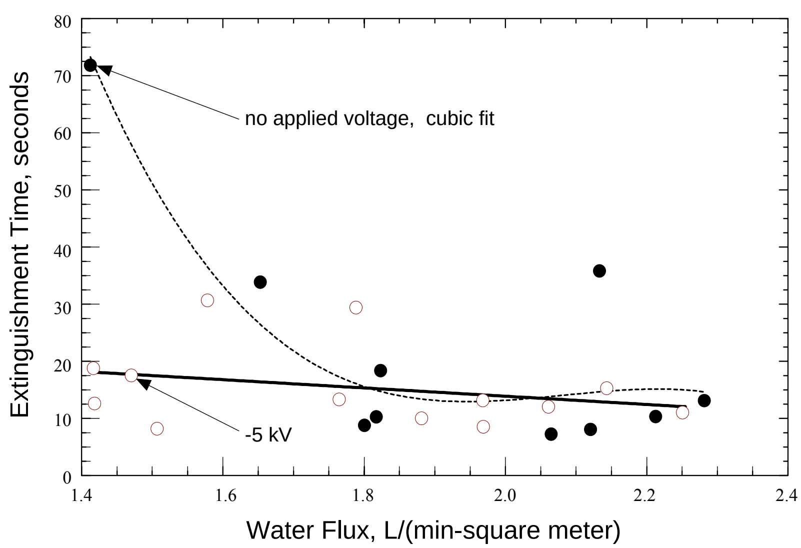


Figure 10. Initial Data on Effect of Electrical Charging for a 10 cm dia. Heptane Fire

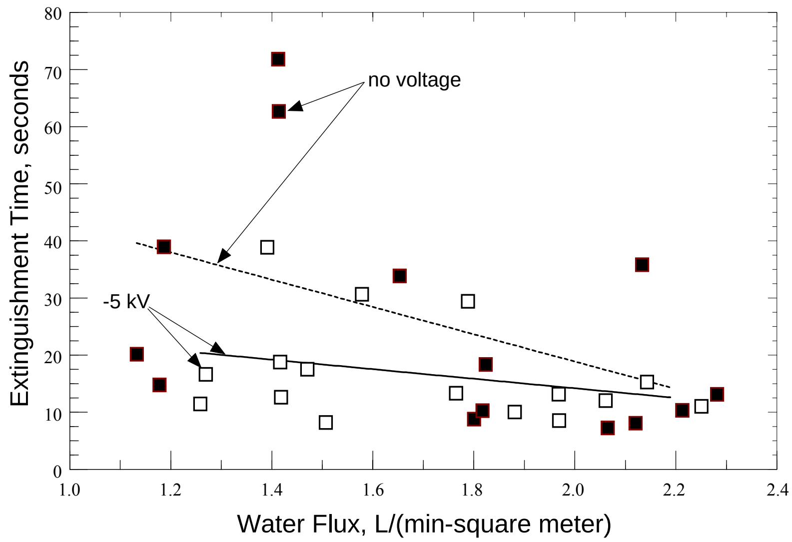
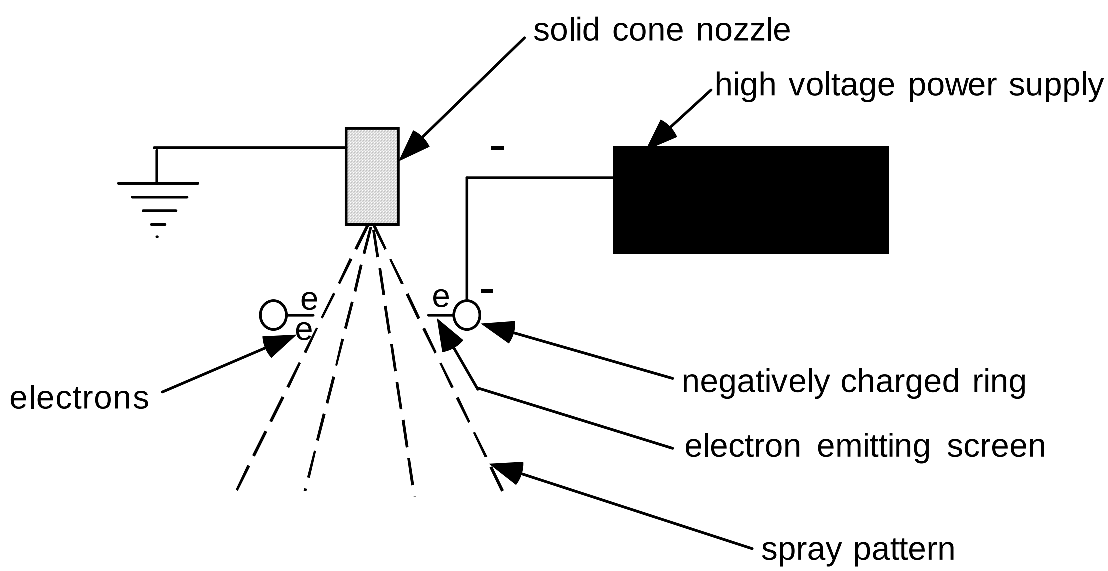


Figure 11
All of
Electrical Charging Data for a 10 cm dia. Heptane Fire



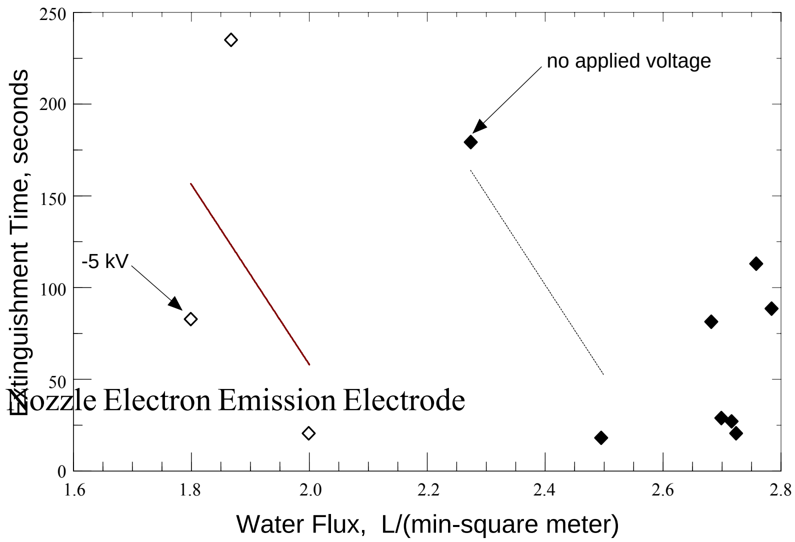


Figure 12 Single Nozzle Electron Emission Electrode

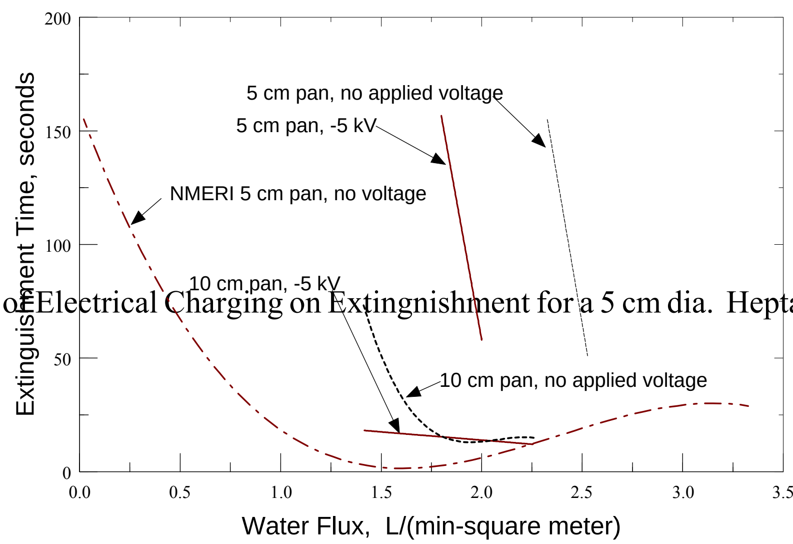


Figure 13 Effect of Electrical Charging on Extingnishment for a 5 cm dia. Heptane Fire

Figure 14. AeroChem 5 and 10 cm and NMERI 5 cm Heptane Extinguishment Data
Hughes Associates, Inc. 10 cm tests range from 5 to 7 L/(min-m^2)